CONTROL STRATEGIES AND APPLICATIONS OF THREE-PHASE DIRECT MATRIX CONVERTERS

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Title of Thesis:

CONTROL STRATEGIES AND APPLICATIONS OF THREE-PHASE DIRECT MATRIX CONVERTERS

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DECLARATION

I declare that this thesis is submitted in fulfilment of the requirements for the ward of PhD degree in the Faculty of Engineering and Information Technology at the University of Technology Sydney. I certify that the work in this thesis has not been previously submitted, in part or whole, to any organizations for a degree or other qualifications.

This dissertation is the result of my own original work and the collaboration is fully acknowledged in this thesis. The literature and information sources used in this thesis are indicated.

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ABSTRACT

AC-to-AC converters have been widely used in various areas in the real world. In industrial applications, the AC-to-AC power conversion is usually accomplished by indirect converters. In these traditional converters, AC power is firstly converted into DC power by a rectifier, and then the DC power is converted into AC power by an inverter. The rectifier and inverter are usually connected via an intermediate bulky DC-link capacitor. The use of the DC-link capacitor in these converters makes the equipment volume bulky, reduces the lifetime, increases the design complexity and decreases the system efficiency. Therefore, it is of great benefit to remove the bulky DC-link capacitor or propose new converter topologies. A matrix converter (MC) does not require large energy storage elements and it has emerged as a potential solution to AC-to-AC conversion.

A three-phase direct MC comprises nine bidirectional semiconductor switches arranged in a 3×3 matrix form to realize the direct AC-to-AC conversion. Thanks to benefits such as bidirectional power flow, compact volume, controllable input power factor and sinusoidal waveform, MCs have attracted research interests and plenty of projects on MC have been reported. MC is also regarded as an all-silicon converter. However, there are some drawbacks associated with MCs and they have very limited industrial applications. These drawbacks include low voltage transfer ratio (VTR), sensitivity to the grid variations and complex modulation. Some MC application areas need more exploration. The work in this thesis is carried out to contribute to possible solutions to some of the above issues by investigating some control strategies and applications of MCs.

The main contributions included in this work are summarized as follows:

(1) A simple decoupling controller is designed for the MC-based unified power flow controller (UPFC) (MC-UPFC) to regulate the power flow in a transmission system. The controllable regions of the MC-UPFC are also analyzed. A design procedure for the closed-loop controller in the MC-UPFC is presented.

(2) A modified PI controller is proposed for the improvement of the steady-state performance by including a current feedforward path. More control flexibility is provided because of the feedforward controller. A PR controller is designed for the MC and this has good performance.

(3) A hysteresis current controller is proposed for the MC to drive AC motors. Both fixed-band and sinusoidal-band hysteresis controllers are investigated, and their performance is compared. The hysteresis controller is a very simple and practical controller for the MC. For the MC-based motor drive, a direct torque control (DTC) technique is also investigated.

(4) Model predictive control (MPC) is investigated to control the MC. This scheme is used in an MC-based microgrid. In the islanded mode, predictive voltage control is employed to regulate the MC output voltages to supply various loads. An improved VTR is observed. When the microgrid is connected to the utility grid, power flow is the main objective. The performance of the controller is tested under various conditions including input disturbance and different loads.

(5) An MC prototype is built to support the research. The prototype hardware includes main circuit, drives, supplies, analog to digital conversion (ADC) conditioning circuits, and sensor board. The algorithm is implemented in Matlab Simulink with C2000 hardware support packages for TI DSP processors. Various experimental tests are carried out to support the proposed strategies.

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1. Published Journal Papers

[1] **J. Zhang**, H. Yang, T. Wang, L. Li, D. G. Dorrell, D.D.C. Lu, "Field-Oriented Control based on Hysteresis Band Current Controller for a Permanent Magnet Synchronous Motor driven by a Direct Matrix Converter," IET Power Electronics, vol. 11, no. 7, pp. 1277-1285, 2018.

[2] **J. Zhang**, L. Li, D. G. Dorrell, Y. Guo, "Decoupling Controller Design and Controllable Regions Analysis for the Space Vector Modulated Matrix Converter-Unified Power Flow Controller in Transmission Systems," Electric Power Components and Systems, vol. 46, no. 1, pp. 1-14, 2018.

[3] **J. Zhang**, L. Li, D. G. Dorrell, "Control and Applications of Direct Matrix Converters: A Review," Chinese Journal of Electrical Engineering, vol. 4, no. 2, pp. 18-27, 2018.

2. Submitted Journal Papers

[4] **J. Zhang**, L. Li, D. G. Dorrell, M. Norambuena, and J. Rodriguez, "Predictive Voltage Control of Direct Matrix Converter with Improved Output Voltage for the Renewable Microgrid Applications," IEEE Journal of Emerging and Selected Topics in Power Electronics, under review, 2018.

[5] **J. Zhang**, L. Li, D. G. Dorrell, "Improved Steady-State Performance by Modified PI Controller and Comparison with PR Controller on Direct Matrix Converters," IET Power Electronics, under review, 2018.

[6] **J. Zhang**, M. Norambuena, L. Li, J. Rodriguez, D. G. Dorrell, "Sequential Model Predictive Control of Three-Phase Direct Matrix Converter," IEEE Access, under review. 2018.

3. Published Conference Papers

[7] **J. Zhang**, L. Li, L. Zhang, D. G. Dorrell, "Hysteresis Band Current Controller based Field-Oriented Control for an Induction Motor driven by a Direct Matrix Converter," 43rd Annual Conference of the IEEE Industrial Electronics Society (IECON 2017), Beijing, China, pp. 4633-4638, November 2017.

[8] **J. Zhang**, L. Li, T. He, M. M. Aghdam, D. G. Dorrell, "Investigation of Direct Matrix Converter Working as a Versatile Converter (AC/AC, AC/DC, DC/AC, DC/DC Conversion) with Predictive Control," 43rd Annual Conference of the IEEE Industrial Electronics Society (IECON 2017), Beijing, China, pp. 4644-4649, November 2017.

[9] **J. Zhang**, L. Li, Z. Malekjamshidi and D. G. Dorrell, "Predictive Voltage Control of Direct Matrix Converter with Reduced Number of Sensors for the Renewable Energy and

Microgrid Applications," 2017 IEEE Energy Conversion Congress and Exposition (ECCE 2017), Cincinnati, U.S., pp. 3309-3315, October 2017.

[10] **J. Zhang**, L. Li, D. G. Dorrell and Y. Guo, "Space Vector Modulation based Proportional Resonant Current Controller with Selective Harmonics Compensation for Matrix Converter Systems," 20th International Conference on Electrical Machines and Systems (ICEMS 2017), Sydney, Australia, August 2017.

[11] **J. Zhang**, L. Li, D. G. Dorrell and Y. Guo, "A PI Controller with Current Feedforward to Improve the Steady-State Error Performance for the Current Controlled Direct Matrix Converter," 20th International Conference on Electrical Machines and Systems (ICEMS 2017), Sydney, Australia, August 2017.

[12] **J. Zhang**, L. Li, D. G. Dorrell and Y. Guo, "Direct Torque Control with a Modified Switching Table for a Direct Matrix Converter based AC Motor Drive System," 20th International Conference on Electrical Machines and Systems (ICEMS 2017), Sydney, Australia, August 2017.

[13] **J. Zhang**, L. Li and D. G. Dorrell, "D-q coupling suppressed pid controller for the transmission line power flow control using a matrix converter," The 42nd Annual Conference of IEEE Industrial Electronics Society (IECON 2016), pp. 6249 – 6254, Florence, Italy, October 2016.

[14] **J. Zhang**, D. G. Dorrell and L. Li, "Applications of the Direct Space Vector Modulation Controlled Matrix Converter as the Unified Power Flow Controller," The 8th International Conference on Power Electronics, Machines and Drives (PEMD 2016), pp. 1-6, Glasgow, UK, 2016.

[15] **J. Zhang**, D. G. Dorrell, L. Li and A. Argha, "A novel sliding mode controller for DC-DC boost converters under input/load variations," The 41st Annual Conference of IEEE Industrial Electronics Society (IECON 2015), pp. 1698-1703, Yokohama, Japan, 2015.

4. Submitted Conference Papers

[16] **J. Zhang**, L. Li, D. G. Dorrell, J. Rodriguez and M. Norambuena, "Investigation of Grid-Connected and Islanded Direct Matrix Converter for the Renewable Microgrid Applications with Model Predictive Control," 2018 IEEE Energy Conversion Congress and Exposition (ECCE 2018), Portland, U.S., accepted, 2018.

[17] **J. Zhang**, L. Li, D. G. Dorrell, J. Rodriguez and M. Norambuena, "Sequential Model Predictive Control of Direct Matrix Converter without Weighting Factors," 44th Annual Conference of the IEEE Industrial Electronics Society (IECON 2018), Washington, U.S., accepted, 2018.

LIST OF ABBREVIATIONS AND ACRONYMS

AC	=	Alternating Current
ADC	=	Analog to Digital Converter
DC	=	Direct Current
DSP	=	Digital Signal Processor
DTC	=	Direct Torque Control
ePWM	=	Enhanced Pulse Width Modulator
eQEP	=	Enhanced Quadrature Encoder Pulse
FACTS	=	Flexible Alternating Current Transmission System
FFT	=	Fast Fourier Transform
F-HB	=	Sinusoidal Hysteresis Band
FOC	=	Field Oriented Control
HB	=	Hysteresis Band
IGBT	=	Insulated Gate Bipolar Transistor
KCL	=	Kirchhoff Current Law
KCL	=	Kirchhoff Current Law
MC	=	Matrix Converter
MC-UPFC	=	Matrix Converter based Unified Power Flow Controller
MPC	=	Model Predictive Control
PI	=	Proportional Integral
PICF	=	Proportional Integral Controller with Current Feedforward
PI-SVM	=	Proportional Integral Controller based on Space Vector Modulation
PLL	=	Phase Locked Loop
PMSM	=	Permanent Magnet Synchronous Machine
PR	=	Proportional Resonant
PRHC-SVM	=	Proportional Resonant Controller with Harmonics Compensator based on Space Vector Modulation
PR-SVM	=	Proportional Resonant Controller based on Space Vector Modulation
PWM	=	Pulse Width Modulation
SCI	=	Serial Communications Interface

S-HB	=	Fixed Hysteresis Band
SMC	=	Sliding Mode Control
SSSC	=	Static Synchronous Series Compensator
STATCOM	=	Static Synchronous Compensator
SVM	=	Space Vector Modulation
THD	=	Total Harmonic Distortion
UPFC	=	Unified Power Flow Controller
VSI	=	Voltage Source Inverter
VSR	=	Voltage Source Rectifier
VTR	=	Voltage Transfer Ratio